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INJECTION OF BALLISTIC HOT ELECTRONS AND COOL HOLES IN A TWO-DIMENSIONAL ELECTRON GAS

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We have constructed a novel magnetic spectrometer to study the dynamics of hot electrons and cool missing electron states injected by quantum point contacts in the two-dimensional electron gas of a GaAs–$Al_xGa_{1-x}As$ heterostructure. The mean free path of these quasiparticles is found to be longer than recent theoretical estimates. The injection energy of the particles is found to be anomalously low as the point contact approaches pinch-off, and also for high bias voltages.

We have investigated hot electron transport, for excess energies up to the order of the Fermi energy E_F, in a two-dimensional electron gas (2DEG). This is done by means of a novel electron spectrometer based on an extension of the electron focusing technique [1,2]. The energy of the electrons is acquired on passage through a quantum point contact, a process which occurs on a length scale much shorter than the transport mean free path. In contrast to traditional measurements we can thus determine a local voltage drop in the ballistic transport regime.

Some of our results have been presented previously [3]. In this paper we review these results, give a qualitative explanation, and present additional experimental data. In particular we discuss some new features observed in the focusing spectra for strong positive and negative bias voltages, and an anomalous dependence when the injector point contact is close to pinch-off. The device consists of injector and collector point contacts (bottom inset in fig. 3) separating regions i (injector) and c (collector) from a region s bounded by a flat "mirror". This acts, in conjunction with a perpendicular magnetic field, as an electron spectrometer. The elastic transport mean free path for electrons at the Fermi energy E_F was 9 μm in this device. A four-terminal measurement configuration was used, with a DC bias voltage of several millivolts applied across terminals 1 and 2 in series with a small AC modulation voltage of 100 μV. The differential focusing signal dV_c/dI_i was obtained by measuring the in-phase AC component across terminals 3 and 4 and normalising to the AC injection current I_i. Focusing peaks were seen as a function of magnetic field B with a period B_{focus}, the corresponding electron energy being

$$E_{focus} = (LeB_{focus})^2/8m\,, \tag{1}$$

with $L = 1.5$ μm the point contact separation in our device. At zero bias $E_{focus} = E_F$. In fig. 1 the evolution

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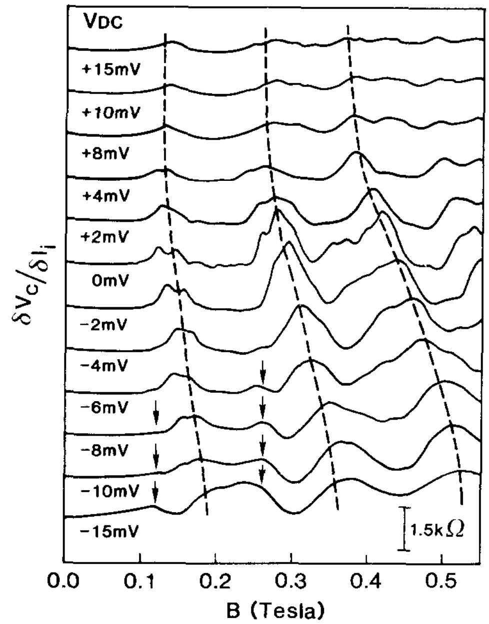

Fig. 1. Electron focusing spectra dV_{34}/dI_{12}, for a range of applied DC bias voltages. The curves have been offset vertically for clarity. The dashed lines indicate the shift of the focusing peaks as a consequence of electron acceleration and deceleration over the point contact region. The arrows point to additional peaks observed for strong bias voltages.

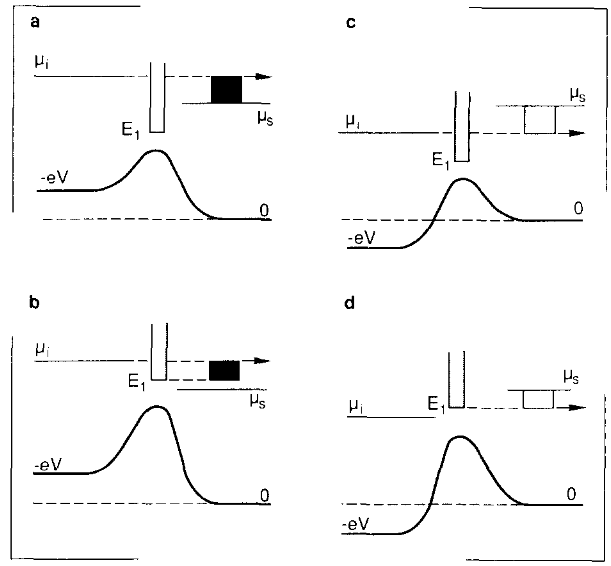

Fig. 2. Schematic drawing of the injection of hot electrons over a point contact (in black) or of cool holes (in white) into the wide 2DEG region s. The local Fermi energies are denoted by μ_i and μ_s in regions i and s respectively. The lowest 1D subband is indicated by the shaded column with subband bottom E_1. The arrows denote the energy selected primarily in a differential focusing experiment.

of the focusing spectrum for a wide range of bias voltages V_{DC} is shown for the case where only one subband was occupied in both the injector and collector point contacts. The increase in energy of the injected electrons with increasing negative DC bias shows up as an appreciable shift of the position of the focusing peaks. For positive DC bias focusing peaks are seen as well, corresponding to the injection of cool missing electron states below the Fermi energy (we refer to these as "holes" here for convenience). Although the injected electron energy distribution for finite negative bias extends over a wide range of energies from E_F to $E_F - eV$, the differential technique selects primarily those electrons with maximal (electrons) or minimal (holes) injection energy. This can be understood on the basis of fig. 2. The point contact is modeled as an energy barrier and a geometrical constriction. We define chemical potentials μ_i and μ_s in the broad 2DEG regions i and s respectively. Note that a negative voltage implies a flow of electrons from region i into region s (panels a and b in fig. 2). In this case the electrons contributing to the AC modulation signal on the collector are primarily the hottest electrons above the Fermi energy (indicated by arrows). Focusing peaks are also seen for positive injection voltages, corresponding to electron injection from region s to region i, and hole injection from region i to region s. The focusing signal is then carried by the coolest holes (c and d in fig. 2). In the case where the bottom of the lowest subband in the point contact (E_1 in fig. 2) rises above μ_i or μ_s an additional bound is imposed on the energy of injected quasi-particles (figs. 2b and 2d) and this can affect the differential focusing signal.

The energy E_{focus} obtained from the position of the third focusing peak is illustrated in fig. 3. A least-squares fit in the linear regime between -8 and $+3$ mV yields

$$E_{focus} = -0.68eV_{DC} + 14.4 \text{ meV}. \tag{2}$$

At zero bias E_{focus} is close to the Fermi energy estimated from the Shubnikov–de Haas oscillations ($E_F \approx 14$ meV). Note that the local electron energy

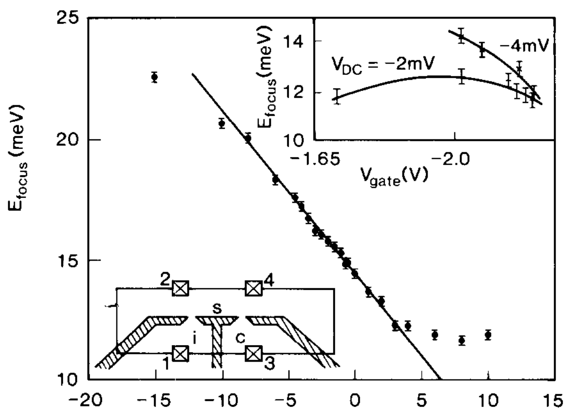

Fig. 3. Spectrometer energy E_{focus} extracted from the focusing peak spacing as function of applied DC bias voltage. The error bars shown reflect the estimated uncertainty in the measurement of the peak position. The top inset shows the dependence of the measured injection energy on the injector gate voltage for a constant DC bias V_{DC} of -2 and -4 mV for a different device. The lines are to guide the eye. Note that the point contact resistance increases with negative gate voltage. The bottom inset is a schematic device diagram. The shaded parts indicate the gate used to define the point contacts and the 2DEG boundary, and the squares denote the ohmic contacts.

gain on crossing the point contact is only $-0.68eV_{DC}$. Since the total sample resistance was 19.4 ± 0.3 kΩ, including a series resistance originating in the ohmic contact region, our measurements imply an injector point contact resistance of 13.2 ± 0.3 kΩ, in good agreement with the quantized resistance [4,5] of a ballistic quantum point contact with a single occupied one-dimensional subband $h/2e^2 = 12.9$ kΩ. In this regime, the maximum injection energy is thus $E_F - eV$ as expected on the basis of fig. 2. As discussed in ref. [3] this constitutes a unique method to measure the local voltage drop near the injector point contact, information which cannot be obtained using conventional conductance measurements [6].

In this device hot electrons travel $\pi L/2 = 2.3$ μm between injector and collector. From theoretical work [7] we estimate that the mean free path of electrons 50% above a Fermi energy of 14 meV should be limited to about 400 nm as a result of electron–electron interaction effects, which should lead to a two order of magnitude reduction in the focusing peak height. Such a short mean free path can be excluded on the basis of our data. Even stronger limits have been placed on the hot electron mean free path recently by Sivan, Heiblum and Umbach using a quite different experimental technique [8]. This discrepancy calls for a reinvestigation of the theory of hot carrier relaxation.

Above +3 mV no clear shift in the peak position is observed and the peak height is considerably reduced (figs. 1 and 3). This may be due to the occurrence of the situation in fig. 2d where the cold hole energy is bounded by E_1, the bottom of the lowest one-dimensional subband. Alternatively the lowest energy of the injected cold holes may be below the collector barrier height. Note that these two mechanisms will not play a role for hot electron injection, which would account for the observed asymmetry between positive and negative biases (fig. 3).

For hot electron injection the peak shift is in agreement with eqs. (1) and (2) down to about -8 mV. For stronger DC biases E_{focus} increases more weakly with V_{DC}. In addition there is some evidence for new peaks in the focusing spectra, with positions corresponding roughly to injection of electrons with the Fermi energy (compare the arrows in fig. 1 with the focusing spectra for $V_{DC} = 0$). These two features may be indicative of a rapid energy relaxation process close to the injector point contact. We stress that the observation of well defined peaks in our experiment precludes relaxation on length scales longer than the cyclotron radius as a possible explanation.

We have also studied the effect of the injector gate voltage on the energy of the injected quasi-particles. The top inset in fig. 3 shows the dependence of the spectrometer energy on gate voltage for a constant V_{DC} of -2 and -4 mV. These data were taken on a different device, with an estimated Fermi energy $E_F \approx 13$ meV. The injection energy measured for $V_{DC} = 0$ was 11.4 meV and did not vary with gate voltage. The discrepancy of 14% between these two numbers may reflect a small uncertainty in the determination of L (of about 7%). The highest energy measured in the spectrometer for a given V_{DC} occurred at a gate voltage of -2.02 V corresponding to one one-dimensional subband being present in the point contact. For smaller gate voltages E_{focus} increased with the point contact resistance, consistent with a lower fraction of the total voltage falling over the point contact because of a lower ratio of point contact resistance to total sample resistance. However, for voltages more negative than -2.02 V, as the injector point contact approached pinch-off (corresponding to electron tunneling through the quantum point contact), E_{focus} decreased as the point contact resistance increased. This anomalous behaviour has also been observed in other devices. Note that this effect is not due to a change in the effective device geometry near pinch-off as it is not observed for the case $V_{DC}=0$. If E_{focus} in this experiment is still equal to E_F-eV, with V the voltage drop across the point contact, then this observation would imply that the background resistance increases dramatically as we pinch the point contact off, which seems unlikely. It is possible that, in this gate voltage regime, E_{focus} was less than E_F-eV, because of inelastic scattering in the point contact region leading to a partial relaxation of the non-equilibrium distribution. Finally, tunneling through the barrier in the injector may affect the energy or angular distribution of the injected electrons, both of which would affect the peak position. Further experimental work is needed to resolve these questions.

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